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A SIMPLE MODEL OF PROTON DAMAGE IN GaAs SOLAR CELLS

John W. Wilson, Gilbert H. Walker, and R. A. Outlaw

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National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

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NOMENCLATURE

a_o	Bohr's radius, 5.29×10^{-5} μm
$D(E)$	total number of displacements per proton of energy E
$D_v(E)$	number of displacements per unit volume, μm^{-3}
E	proton energy, KeV
E_D	displacement damage threshold, eV
E_R	Rydberg's constant, 13.6 eV
$f(\mu)$	efficiency for diffusion to junction along direction defined by μ
$F(x)$	efficiency function for diffusion from depth x to the junction
$\ell_D(E)$	displacement mean free path for proton of energy E, μm
L	minority carrier diffusion length, μm
M_2	average mass of gallium and arsenic nucleus, amu.
n	nuclear density in GaAs crystal, μm^{-3}
p	distance traveled along proton path, μm
$P(E)$	pathlength of proton of energy E, μm
r	minority carrier rms distance traveled before recombination, μm
$R(E)$	average projected range of a proton of energy E, μm
T	energy transfered to struck nucleus, keV
T_m	maximum energy transferred to struck nucleus, keV
x	penetration depth into solar cell, μm
Z_2	average charge number of GaAs nucleus
$\Delta\eta$	change in collection efficiency
λ	photon absorption pathlength, μm
μ	cosine of direction of diffusion in reaching junction
$\bar{\mu}(E)$	average direction cosine of scattered proton of energy E

$\nu(E)$	average number of displacements formed by one proton scattering event
$\xi_D(E)$	number of displacements per unit pathlength for a proton of energy E, $(\mu m)^{-1}$
$\rho(x)$	cell collection efficiency for a normal unirradiated cell, μm^{-3}
$\sigma_D(E)$	displacement cross section for protons, μm^2
σ_r	recombination cross section, μm^2

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SUMMARY

A simple proton damage model for GaAs solar cells is derived and compared to experimental values of change in short circuit currents. The recombination cross section associated with the defects was determined from the experimental comparison to be $\approx 1.2 \times 10^{-13}$ cm^2 in fair agreement with values determined from the deep level transient spectroscopy technique.

Introduction

Gallium arsenide solar cells have received considerable attention due to their potential usefulness in high-power space-energy systems as well as special space probe applications where high operating temperature is a factor (ref. 1). However, space radiation damage to the cell may be a limiting factor. Consequently, radiation damage experimental studies have been conducted and the present report is an attempt to develop a simple model in which these experimental results can be understood.

Earlier models for electron radiation damage assumed the defects to be produced uniformly throughout the cell volume, and modeled the cell performance in terms of cell-averaged diffusion lengths of the minority carriers (refs. 2 and 3). In view of the short pathlengths of the protons used in radiation damage studies and the specific dependence of the cell efficiency on the proton energy, the assumption of uniform damage within the cell seems unwarranted for low-energy proton exposure. Consequently, the present report treats geometric distribution of the displacement damage in detail and cell performance is not treated by a cell-averaged parameter such as diffusion length. Cell performance is evaluated in terms of the cell-averaged minority carrier recombination probability in diffusion to the junction of the cell. The average of the minority recombination probability over the cell active region weighted according to the solar-averaged photoabsorption rate is used to estimate the decrement in the short circuit current.

Theory of Defect Formation

Atomic displacements caused by proton impact with atomic nuclei result in crystal defects. The formation rate of these defects is related to Rutherford's cross section (ref. 4)

$$\sigma_D(E) = \frac{4\pi\, a_o^2\, E_R^2\, Z_2^2}{M_2 E} \left(\frac{1}{E_D} - \frac{1}{T_m}\right) \tag{1}$$

where a_o is Bohr's radius, E_R is Rydberg's constant, Z_2 is the atomic number of the struck nucleus, M_2 the corresponding nuclear mass number, E is the proton kinetic energy, E_D is the energy required to displace the nucleus from it's lattice site, and T_m is the maximum energy transfer in the collision

$$T_m = \frac{4M_2}{(1 + M_2)^2}\, E \tag{2}$$

The threshold for displacement requires $T_m > E_D$. The value of $E_D = 25$ eV insures that only close collisions result in displacement so that screening corrections to the Rutherford formula are unimportant (ref. 4). If the atomic recoil energy is sufficiently large ($T \gg E_D$) then additional displacements can be produced by the recoiling nucleus before coming to rest at an interstitial site. The average number of recoils produced by one initiating proton collision event is given as a function of the maximum energy transfer by

$$\bar{\nu}(E) = \begin{cases} 1 + \dfrac{T_m}{2\,(T_m - E_D)} \log\,(T_m/E_D) \; ; & T_m > 2E_D \\ 1.0 \; ; & 2E_D \geq T_m > E_D \end{cases} \tag{3}$$

assuming half of the recoil energy produces further displacements and the other half is dissipated in other processes (ref. 4). These quantities allow the calculation of the number of displacements produced per unit distance traveled by a proton of fixed energy.

In passing through a crystal, most of the energy of a proton is transferred to orbital electrons (ref. 5). The pathlength traveled in coming to rest is found by fitting the data of reference 5 as

$$P(E) = 0.077\, E^{0.5} + 1.125 \times 10^{-4}\, E^{1.64} \tag{4}$$

where E is in keV and P is in μm. As derived from slowing down theory, a unique value of kinetic energy can be associated with each position along a proton's trajectory. The proton energy as a function of the distance P yet to be traveled before coming to rest is given by

$$E = 209.6\ P^{2.08}/(1 + 1.055\ P^{1.43}) \quad (5)$$

as determined from the stopping power data of Andersen and Ziegler (ref. 5). In coming to rest, the proton undergoes multiple scatterings from atomic nuclei (of which a few result in displacements) which alters ever so slightly its direction of motion. The depth of penetration R and pathlength P are approximately related by (ref. 5)

$$P^{-1}\ R = [1 - \exp\ (-\ 0.084\ E^{0.55})] \quad (6)$$

This ratio is related to the average deviation in the direction of motion and is most important at low energies. The average depth of penetration and initial energy as related through equations (4) and (6) can be approximated by

$$R(E) = 0.0062\ E + 2.92 \times 10^{-5}\ E^{1.77} \quad (7)$$

There is no unique energy associated with a given depth of penetration due to multiple scattering. However, the average energy of protons which penetrate and stop at a depth R is

$$E = 593\ R^{1.5}/(1 + 3.71\ R^{0.5}) \quad (8)$$

The above quantities were used to determine the displacement density within a GaAs crystal.

A proton of energy E_0 incident on the face of the crystal will travel a distance

$$P_0 = P(E_0) \quad (9)$$

before coming to rest. After traveling a distance p the energy will be reduced to

$$E = 209.6\ (P_0 - p)^{2.08}/[1 + 1.055(P_0 - p)^{1.43}] \quad (10)$$

At this position p the displacement mean free path is

$$\ell_D(E) = 1/n\ \sigma_D(E) \quad (11)$$

where n is the density of scattering centers in the crystal ($4.42 \times 10^{10}/\mu m^3$) and σ_D is the displacement cross section averaged for GaAs ($M_2 = 72.5$ and $Z_2 = 32$). The average number of displacements per unit pathlength is

$$\xi_D(E) = \overline{\nu}\ (E)/\ell_D(E) \quad (12)$$

The use of equations (10) and (12) allow appropriate partitioning of the proton's energy into electronic excitation and displacements everywhere along its path.

The number of displacements along the protons path is now to be related to the displacement damage in the crystal. For normal incident protons of energy E_o on the face of a crystal, the number of displacements along its path are given by equations (10) and (12). However, by the time its energy is reduced to E, it has penetrated to an average depth x given by

$$x = R(E_o) - R(E) \tag{13}$$

The pathlength and penetration depth are related to the average direction cosine (ref. 6) and is approximated here by finding the ratio $\bar{\mu}(E) = dP(E)/dR(E)$ using equations (4) and (6). In terms of $\mu(E)$, the average number of displacements per unit depth is

$$\frac{dD}{dx} = \bar{\mu}(E)\ \varepsilon_D(E) \tag{14}$$

where x is found from relation (13). The effects of multiple scattering are demonstrated in fig. 1. The results of equation (14) for the average proton path is shown as the full line in comparison to calculations neglecting multiple scattering according to equation (12) shown as the dashed line.

The total number of displacements formed along the path of a proton with initial energy E_o is

$$D(E_o) = \int_o^{E_o} \varepsilon_D(E)\ \frac{dP}{dE}\ dE \tag{15}$$

The numerical evaluation of equation (15) is found to be

$$D(E_o) = \begin{cases} 0 & E_o \leq .728 \\ 1.6 + 14.5(1 + 0.005\ E_o^{0.68})\ \log_{10} E_o & E_o > .728 \end{cases} \tag{16}$$

where the threshold displacement energy for the proton is 0.728 MeV. Equation (15) was also evaluated using the displacement theory of Lindhard, Scharff and Schiott (LSS) as discussed in reference 7. The numerical values are shown in comparison to equation (16) in figure 2.

It is assumed that these displacements form recombination centers for electron-hole pairs produced by photon absorption. A pair once formed undergoes thermal diffusion until it recombines or is separated at the junction. The relation between the rms distance traveled in moving to a position a distance L away from the source point is (ref. 8)

$$\bar{r} = \sqrt{6}\, L \tag{17}$$

If σ_r is the recombination cross section and L the distance along an arbitrary straight line path to the junction, then the fractional loss of pairs due to recombination in reaching the junction along a fixed direction is

$$f(\mu) = \begin{cases} [1 - \exp(-\int_{x_j}^{x} \sigma_r\, D_v(x)\sqrt{6}\, dx/\mu)] & x > x_j \\ [1 - \exp(-\int_{x}^{x_j} \sigma_r\, D_v(x)\sqrt{6}\, dx/\mu)] & x < x_j \end{cases} \tag{18}$$

where μ is the cosine of the direction to the junction. Averaging the fractional loss over all directions towards the junction

$$F(x) = \int_0^1 f(\mu)\, d\mu \tag{19}$$

and noting

$$\int_x^{x_j} D_v(x)dx = \phi[D(E_x) - D(E_j)] \tag{20}$$

where $D_v(x)$ is displacement density and ϕ is the proton fluence results in

$$F(x) = \begin{cases} 1 - E_2\,[-\sqrt{6}\, \sigma_r\, \phi\, (D(E_x) - D(E_j))]\,; & E_x > E_j \\ 1 - E_2\,[-\sqrt{6}\, \sigma_r\, \phi\, (D(E_j) - D(E_x))]\,; & E_j > E_x \end{cases} \tag{21}$$

Assuming the trajectory of an average proton as defined by equation (8), E_x and E_j become

$$E_x = \frac{593\, (R_0 - x)^{3/2}}{1 + 3.71(R_0 - x)^{1/2}} \tag{22}$$

and

$$E_j = \frac{593\, (R_0 - x_j)^{3/2}}{1 + 3.71\, (R_0 - x_j)^{1/2}} \tag{23}$$

Complete neglect of multiple scattering effects is accomplished by replacing equations (22) and (23) by

$$E_x = 209.6(P_o - x)^{2.08}/[1 + 1.055(P_o - x)^{1.43}] \quad (24)$$

and

$$E_j = 209.6(P_o - x_j)^{2.08}/[1 + 1.055(P_o - x_j)^{1.43}] \quad (25)$$

If $\rho(x)$ is the normal efficiency function for producing and collecting electron-hole pairs at the junction, then the efficiency change for the proton damaged crystal is

$$\Delta n = \int_0^t \rho(x)\, F(x)\, dx / \int_0^t \rho(x)\, d(x) \quad (26)$$

where t is the maximum depth of the active region of the cell. To simplify the present calculation without serious error, it is assumed that $\rho(x)$ is proportional to the photoabsorption density normalized to unity as

$$\rho(x) = \frac{1}{\lambda} e^{-x/\lambda} \quad (27)$$

where the solar absorption length λ is 0.714 μm (ref. 9).

RESULTS

The geometry of the solar cell is shown in figure 3. The change in the cell current collection efficiency as given by equations (24) and (25) were evaluated numerically for solar cell parameters shown. In traversing the cell, the protons follow neither the trajectory of the average proton nor the trajectory in which multiple scattering is neglected as shown in figure 1. The effects of multiple scattering were estimated by averaging the cell damage for the two functions shown in figure 1 in which some effects of deviations about the average trajectory are included. It is clear that an understanding of the low-energy experimental data requires detailed modeling of multiple scattering effects. The window thickness parameter which varied from cell to cell in experimental tests (refs. 10 and 11) were assumed to be governed by a uniform distribution in the present calculations. The model results averaged over the window thickness are compared to short circuit current measurements in irradiated cells in figure 4. The best value of recombination cross section is found to be

$$\sigma_r = 1.2 \times 10^{-13} \text{ cm}^2$$

which is in fair agreement with the estimated average cross section $\sigma_r = 1.06 \times 10^{-13}$ cm^2 determined from deep-level transient spectroscopy (ref. 12).

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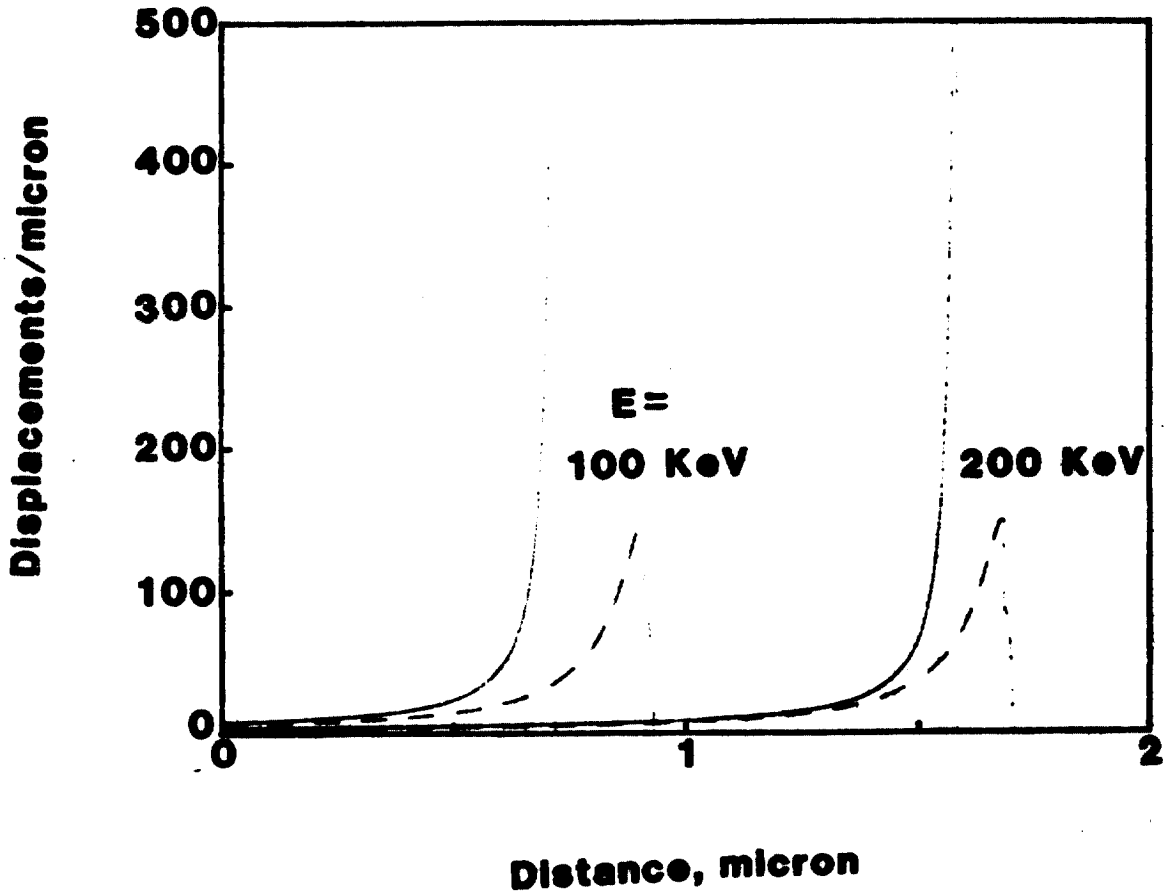


Fig. 1. Displacement density for a single proton passage neglecting multiple scattering effects (----) and assuming an average proton trajectory (——).

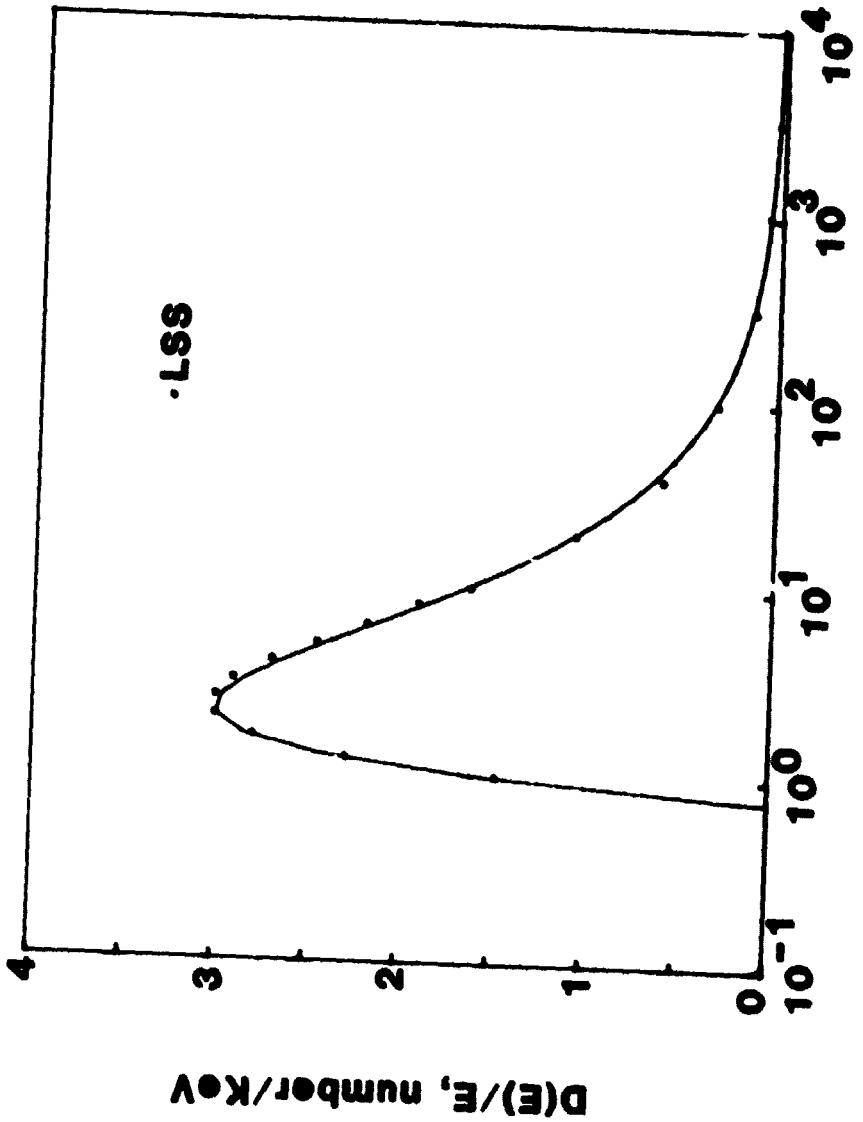
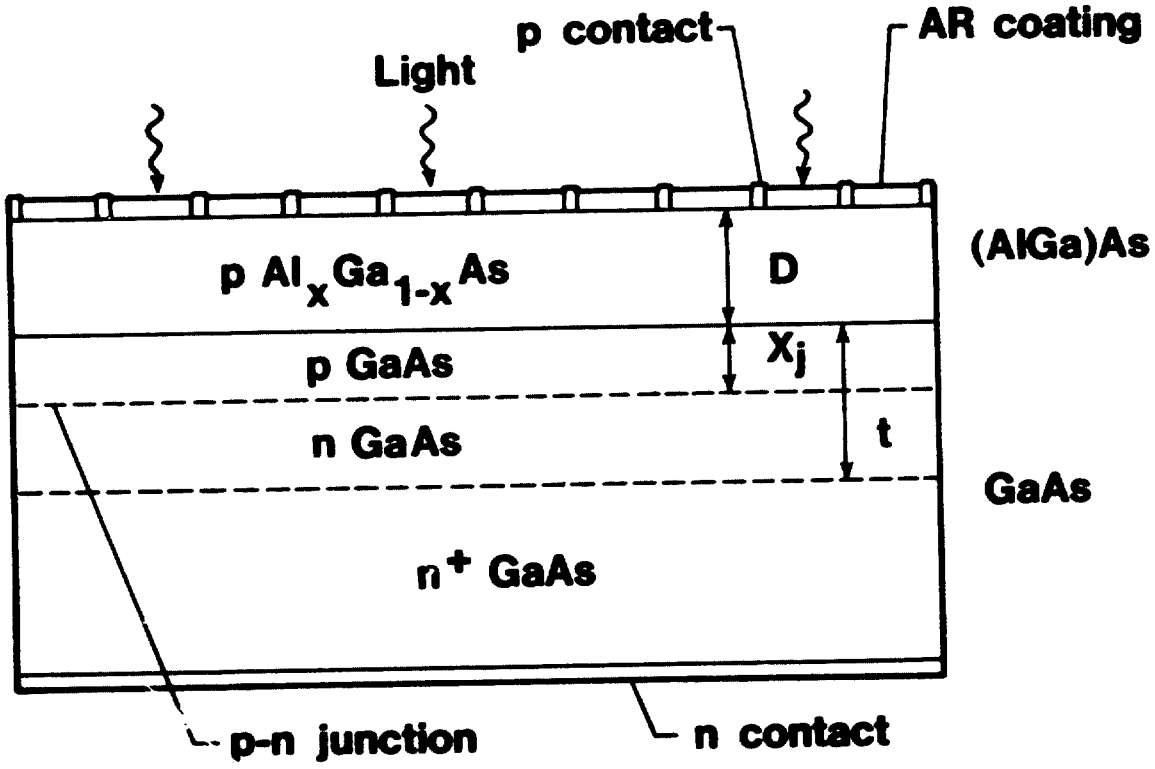


Fig. 2. Displacement yield for a proton in coming to rest in GaAs crystals.



Number of fingers = 24
p contact: Au-Zn-Ag
n contact: Au-Ge-Ni-Ag
AR coating: Ta_2O_x
p $Al_xGa_{1-x}As$: $x \geq 0.85$
Cell size=$2\times2cm^2$

$0.6\mu m \geq D \geq 0.2\mu m$

$X_j = 0.4\mu m$

$t = 1.5\mu m$

Fig. 3. GaAs solar cell structure used in the present model.

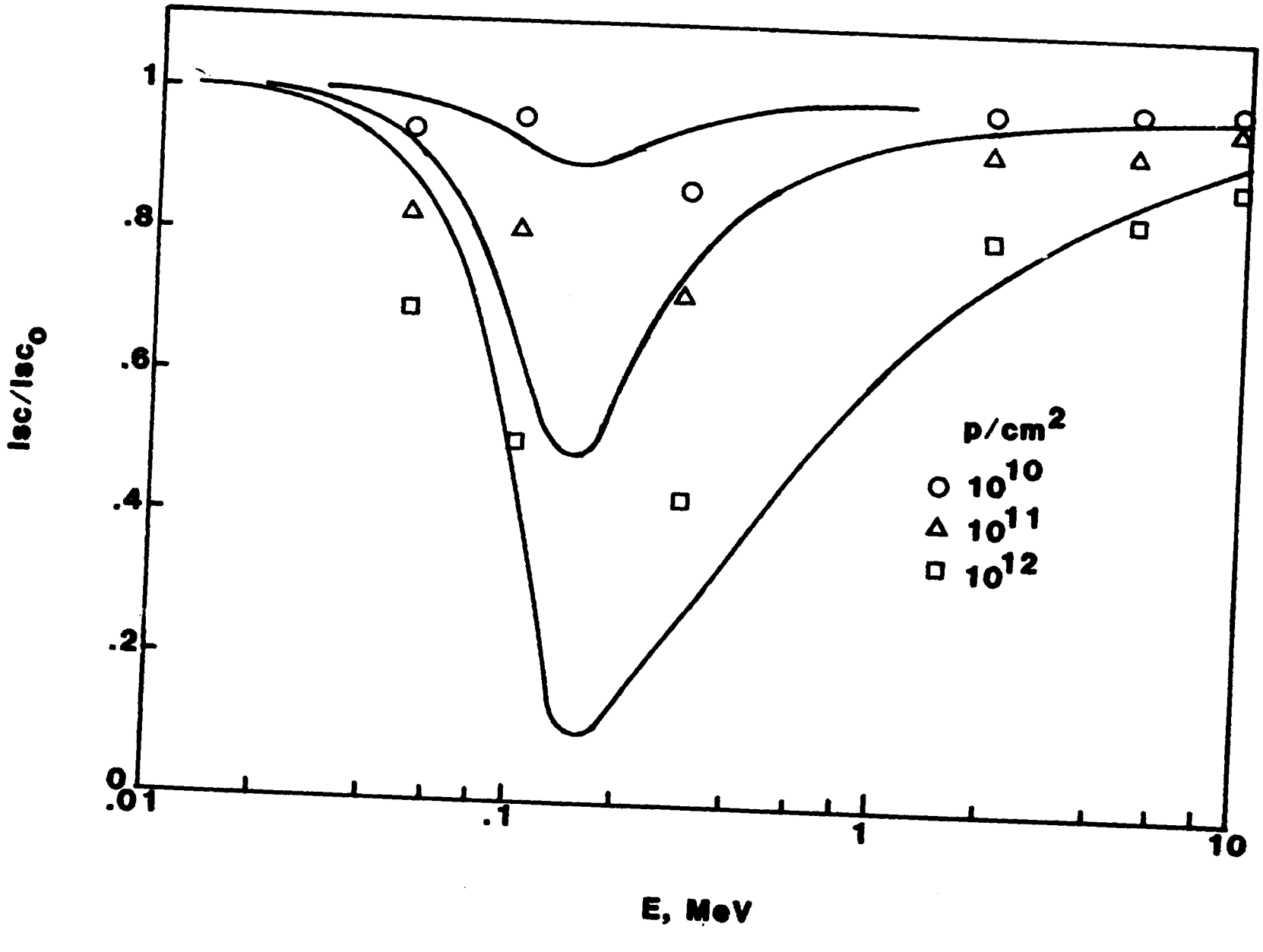


Fig. 4. Comparison of experimental short circuit current changes in proton-damaged solar cells as a function of proton energy.